CHANGE CHARACTERISTICS OF WATER EXCHANGE BETWEEN THE YANGTZE RIVER AND THE DONGTING LAKE DURING 1960–2018 IN CHINA

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(Received 27th Sep 2019; accepted 4th Feb 2020)

Abstract. Hydrological exchange between the trunk stream and the floodplains is the key factor maintaining ecological functioning. The water discharge diverting from the Yangtze River to the Dongting Lake has recently decreased considerably in China. However, their variation characteristics and major driving factors remained unclear. In this study, Mann Kendall trend and Pettitt abrupt tests were employed to determine the changes of time series. Double mass curve analysis and regression analysis were used for the qualitative analysis of the impacts of climate change and human activity. Results revealed that precipitation change trends significantly decreased in autumn. The water discharge at the trunk Yangtze River had a decreasing trend in autumn and an increasing trend in winter. The annual and seasonal water discharge diverting from the Yangtze River to the Dongting Lake, except at Xinjiangkou in summer, exhibited significant downward trends. No consistent trends in precipitation and water discharge were identified, thereby indicating that the seasonal relationships between them had been disturbed by human activities. Human activities had a dominant effect on the water discharge exchange between them during 1967–2018. Along with the intensification of human activities, the hydrological connectivity between the Yangtze River and the Dongting Lake would probably be further changed in the near future.

Keywords: *hydrological connectivity, river–floodplain systems, the Jingjiang Three Outlets, the Three Gorges Dam, Mann–Kendall test, Pettitt test*

Introduction

Floodplains have the highest levels of production and biodiversity worldwide (Tockner and Stanford, 2002) and not only provide habitat and refuge for species (Whited et al., 2007; Hung et al., 2012) but also supply important services for humankind (Kummu et al., 2014). The hydrological exchange between the trunk river and its floodplains is the most important factor for maintaining ecological function and biodiversity and for flood attenuation (Thomaz et al., 2007; Zurbrügg et al., 2012). In recent decades, river floodplain systems have been heavily disturbed by human activities (Heiler et al., 1995; Clilverd et al., 2013). Moreover, the hydrological cycle in major rivers worldwide has undergone dramatic spatiotemporal changes along with global climate changes (Palmer et al., 2008). Hydrological connectivity between the trunk river and its floodplains are changed by human activities and climate change significantly in many large rivers (Heiler et al., 1995; Knowlton and Jones, 1997;

DOI: http://dx.doi.org/10.15666/aeer/1802_31773193

Amoros and Bornette, 2002; Tockner et al., 2010) and caused the biodiversity and bioproduction degradation in many river–floodplain systems, including the Danube in Europe (Besemer et al., 2005), the Missouri in the USA (Knowlton and Jones, 1997), and the Mackenzie in Canada (Lesack and Marsh, 2010). Numerous previous studies have concentrated on the benefits of river floodplain connections (Bullock and Acreman, 2003; Acreman et al., 2003; Zurbrügg et al., 2012). However, the effects of human activities and climate change on hydrological connectivity have not received significant attention. Therefore, quantitative assessments of the influences of human activities and climate change on the hydrological connectivity of these systems are extremely essential to make effective management and conservation plans for river–floodplain ecosystems.

The Yangtze River floodplain is characterized by a number of lakes of various sizes in China (Nie et al., 1999; Yang et al., 2008). The Yangtze River freely connected with many lakes in the history (Ru and Liu, 2013). Along with the intensive human activities such as the construction of dam, deforestation, water diversion, and sand extraction, the hydrological connectivity has been remarkably changed. At present, only three lakes (Dongting Lake, Poyang Lake, and Shijiu Lake) retain direct connections with the Yangtze River. The obstruction of hydrological connectivity changes the patterns of the lake wetland vegetation (Hu et al., 2015), damages the diversity of fish species (Xie et al., 2003), and increases flood risk (Nakayama and Shankman, 2013) in the Yangtze River floodplain. Thus, the obstruction of hydrological connectivity is one of the top threats to the Yangtze River floodplain (Liu and Wang, 2010; Pan et al., 2011).

The hydrological connectivity between the Yangtze River and the Dongting Lake is the most typical and complex in the floodplain of Yangtze River in China (Lai et al., 2014a). The Dongting Lake receives water from the Yangtze River through the tie channels of the Jingjiang Three Outlets (JTO). During 1956–1966, the JTO could recharge averaged 29.3% of the main river water discharge into the Dongting Lake; however, after 2003, it can divert only 11.8% (Zhu et al., 2015). The hydrological connectivity at the JTO has considerably decreased (Ou et al., 2014). Thus, significant attention is paid to investigate the reasons for the decreased hydrological connectivity at the JTO, especially after the Three Gorges Dam (TGD) in 2003. Chang et al. (2010) and Zhu et al. (2015) analyzed the variations in the water exchange at the JTO to determine the TGD influences on the water exchange capability, and they had different opinions on the effect factors of the water exchange changes at the JTO. Zhang et al. (2015a) found that the TGD impoundment was responsible for 31.1% of the decrease in the water exchange at the JTO. Li et al. (2016) found that river channel changes were responsible for 23.6% of the decrease in the water exchange at the JTO after the TGD. However, it still disagrees on how human activities influent the water exchange at the JTO (Chang et al., 2010; Zhu et al., 2015; Zhang et al., 2015a; Li et al., 2016). Furthermore, previous studies mainly focused on the influences of human activities, but the effects of climate change were neglected. The properties of changing water exchange and their influence factors at the JTO were not extensively analyzed. Therefore, this study objectives are as follows: (1) to detect the annual and seasonal variations in the water exchange at the JTO on the basis of the daily hydrologic data during 1960–2018; (2) to quantify the effects of precipitation changes on water exchange; and (3) to assess the contributions of human activities and climate change to water exchange reduction. This study hopes to provide an important scientific basis for the optimization control of the river–lake relationship and the protection of river–floodplain ecosystems.

Study area and data

Study sites

Human activities in the Yangtze River have remarkably intensified during the past half century, especially after the economic reform and opening-up policy was implemented in 1978 in China (Chen et al., 2014). The storage capacity of large reservoirs and dams has significantly increased, especially after 1981 and 2003 (*Fig. 1*). Water–soil conservation (i.e., terracing, planting trees, and protecting vegetation) was implemented in 1988. In 1992, the cumulative area of water–soil conservation displays an upward trend from 156.56 × 10^3 km^2 to 320.58 × 10^3 km^2.

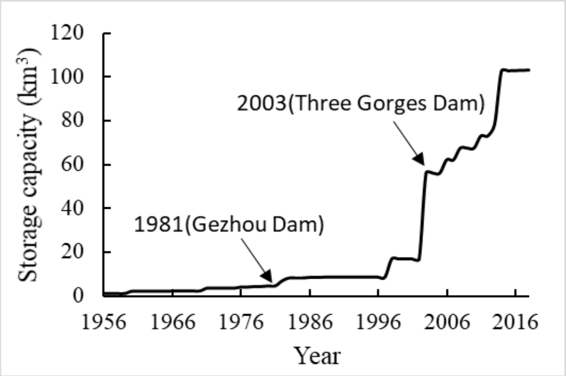

Figure 1. *Storage capacity of large reservoirs in the upper Yangtze River*

Local river channel cut-off events. As shown in *Table 1*, three instances of artificial and natural channel cut-offs occurred in the lower Jingjiang River from 1967 to 1972. Artificial channel cut-off projects at Zhongzhouzi in 1967 and Shangchewan in 1969 were carried out, which respectively shortened the channel lengths of the lower Jingjiang River (the lower Jingjiang River from the Ouchikou to the Chenglingji) to approximately 32.4 and 29.2 km. Natural channel cut-off at Shatanzi occurred in 1972, which resulted in a channel length decrease of 18.95 km.

Table 1. *River channel cut-off events in the lower Jingjiang River. (Data originated from Qin et al., 2013)*

Cut-off name	Cut-off year	Cut-off reason	Channel length before the cut-off (km)	Channel length after the cut-off	Channel length change
Zhongzhouzi	1967	Artificial	36.7	4.3	32.4
Shangchewan	1969	Artificial	32.7	3.5	29.2
Shatanzi	1972	Natural	20.3	1.35	18.95

The Songzi, Taiping, and Ouchi outlets comprise the JTO. The Zhicheng Hydrological Station situated 18 km upstream of the JTO was used to reflect the influence of the mainstream. Zhicheng is approximately 60.8 km distant from Yichang

Hydrological Station that is the hydrological control station of the upper Yangtze River. They have very similar streamflows. Xinjiangkou and Shadaoguan are the hydrological stations at the Songzi outlet. Mituosi Hydrological Station controls the Taiping outlet. Ouchi (kang) and Ouchi (guan) are the hydrological stations at the Ouchi outlet (*Fig. 2*).

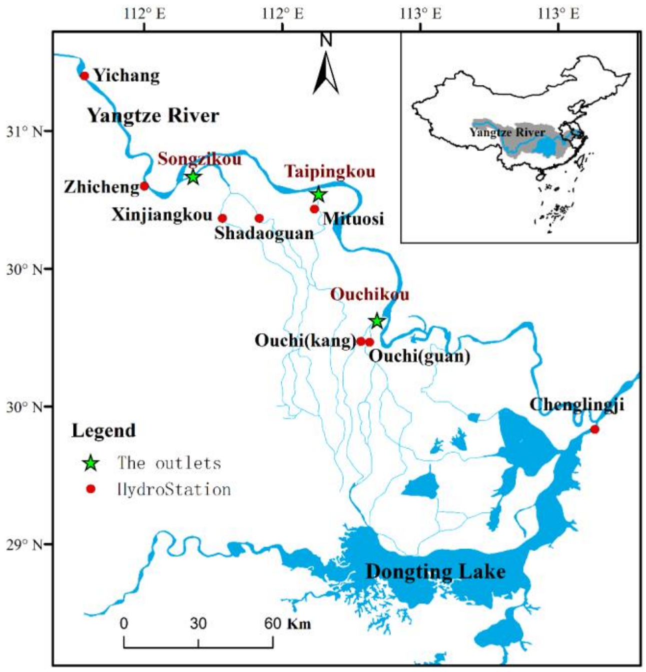

Figure 2. *Geophysical location of the JTO in the Yangtze River Basin*

Data

The daily water level and discharge data during 1960–2018 were obtained from the Bureau of Hydrology, Changjiang Water Resources Commission in China. The data of daily precipitation from 180 meteorological stations situated in the Yangtze River Basin were obtained from the China Meteorological Data Network (http://data.cma.cn/). A total of 70 meteorological stations with continuous precipitation record stations during 1960–2018 are located in the upstream of Zhicheng (*Fig. 3*). Based on the climate features in the Yangtze River Basin, there are four seasons divided: spring between March and May, summer between June and August, autumn between September and November, winter between December and February.

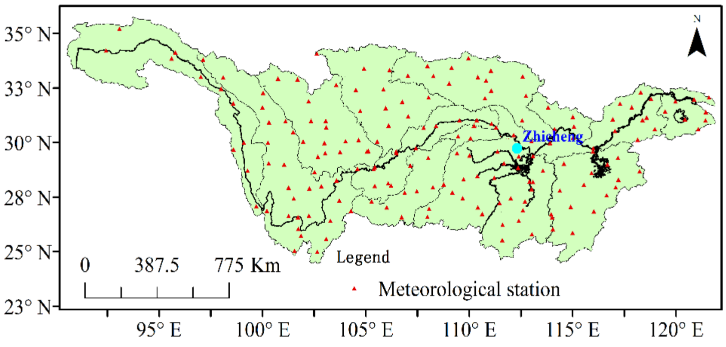

Figure 3. *Spatial distribution of meteorological stations in the Yangtze River Basin*

DOI: http://dx.doi.org/10.15666/aeer/1802_31773193

Methods

Mann–Kendall trend test

The trend analyses which are the hydrological-meteorological time series used the non-parametric Mann–Kendall (MK) test (Mann, 1945; Kendall, 1975). The test statistic for a time series $(x_1, x_2, x_3, \dots, x_n)$ is given as follows:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(x_j - x_i) \tag{Eq.1}$$

$$\mathrm{sgn}(x_j - x_i) = \begin{cases} +1 & \text{if} \quad (x_j - x_i) > 0 \\ 0 & \text{if} \quad (x_j - x_i) = 0 \\ -1 & \text{if} \quad (x_j - x_i) < 0 \end{cases} \tag{Eq.2}$$

where x_i and x_j respectively represent the data values at times i and j. n is the time series length.

$$\mathrm{Var}(S) = \frac{[n(n-1)(2n+5) - \sum_{i=1}^{m} t_i\,(t_i - 1)(2t_i + 5)]b}{18} \tag{Eq.3}$$

where m and t_i respectively represent the number of tied groups and data in the tied group. The standard normal variable Z is given by *Equation 4:*

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var\,(S)}}, & \text{if} \quad S > 0 \\ 0, & \text{if} \quad S = 0 \\ \frac{S-1}{\sqrt{Var\,(S)}}, & \text{if} \quad S < 0 \end{cases} \tag{Eq.4}$$

The positive Z value is an increasing trend, and the negative Z value is a decreasing trend. If $|Z|$ is greater than 1.96 at the 0.05 significance level, the null hypothesis of the absent trend is rejected.

Pettitt abrupt change test

The abrupt change of the hydrological-meteorological time series used the Pettitt test (Pettitt, 1979). The method uses a version of the Mann–Whitney statistic $U_{t,n}$, including two parts $(x_1,\ x_2,\ x_3, \dots, x_t$ and $x_{t+1},\ x_{t+2},\ x_{t+3}, \dots, x_T)$ from the same time series. The test statistic $U_{t,n}$ is computed as follows:

$$U_{t,T} = \sum_{i=1}^{t} \sum_{j=1}^{T} sgn\ (x_t - x_j) \quad \text{for } t = \ 2, \dots, n \tag{Eq.5}$$

The largest $|U_{t,T}|$ value is the abrupt change point

$$K_T = max|U_{t,T}| \tag{Eq.6}$$

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The significance testing are as follows:

$$p \cong 2\exp\left\{-\frac{6(K_T)^2}{T^3+T^2}\right\} \quad \text{(Eq.7)}$$

Once the p value is less than the 5% significance level, a significant abrupt change point exists.

Double mass curve analysis

Double mass curve (DMC) is a common method to test the consistency and variation of the relationship between two parameters. A DMC is a line drawn between the continuous cumulative values of one variable and the continuous cumulative values of another variable for the same period. Generally, the Double mass curve analysis kept a straight line if water discharge was not affected by human activities. Therefore, evident abrupt change points in the DMCs suggest the variations influenced by human activities (Zhao et al., 2017).

Regression analysis for quantifying the influences of human activities and climate change

Reconstruction of the natural water discharge at the JTO is necessary to better understand and quantify the influences of human activities and climate change on hydrological connectivity between Dongting Lake and Yangtze River. The amount of water exchange at the JTO is impacted by various factors, such as the position between the JTO entrance and the trunk stream, the channel scouring and silting changes, and river regime variations in the mainstream (Lu et al., 2012). The changes of relative position and river channel gradually and slowly occur under natural conditions (Zhang et al., 2015b). Thus, the amount of water exchange at the JTO is directly related to the changes of water discharge at the mainstream of Zhicheng. To quantify the impact of precipitation changes and human activities on water exchange at the JTO, the regression analysis method was applied in the current study.

Previous studies indicated that the precipitation and streamflow in the Yangtze River Basin were minimally affected by human activities before the 1970s (Yang et al., 2015; Zhao et al., 2015). Thus, the period 1960–1966 was used as the reference period to achieve the requirement of this study. Although streamflow is related to many factors, such as precipitation, temperature, dam construction, and GDP in the Yangtze River Basin, numerous studies found that precipitation is the most correlated with streamflow at the mainstream which can explain 80% of the variance during the past 50 years (Chen et al., 2014; Zhao et al., 2015). Therefore, regression equations are established between annual precipitation and water discharge at Zhicheng based on data collected in the period 1960–1966 to estimate the natural water discharge at Zhicheng. Afterward, regression equations are established between the water discharge at Zhicheng and the water exchange at the JTO in the period 1960–1966. Thus, water exchange changes at the JTO in response to precipitation change in subsequent years can be quantified by estimating the natural water exchange at Zhicheng. The hydrological response to human activities can be provided by the difference between the estimated and the observed water discharge.

DOI: http://dx.doi.org/10.15666/aeer/1802_31773193

Results and discussion

Annual and seasonal precipitation trends in the basin

The trends of the basin-averaged seasonal and annual precipitation in the upstream of Zhicheng from 1960 to 2018 on the basis of MK test are shown in *Figure 4*. The mean annual precipitation during 1960–2018 was 996.09 mm (from 756.50 mm to 1027.80 mm). Annual precipitation shows an inconspicuous tendency. On a seasonal basis, precipitation trends in spring, summer, and winter present no statistical significance. However, precipitation trends show a remarkable decreasing trend with a 99% confidence level in autumn.

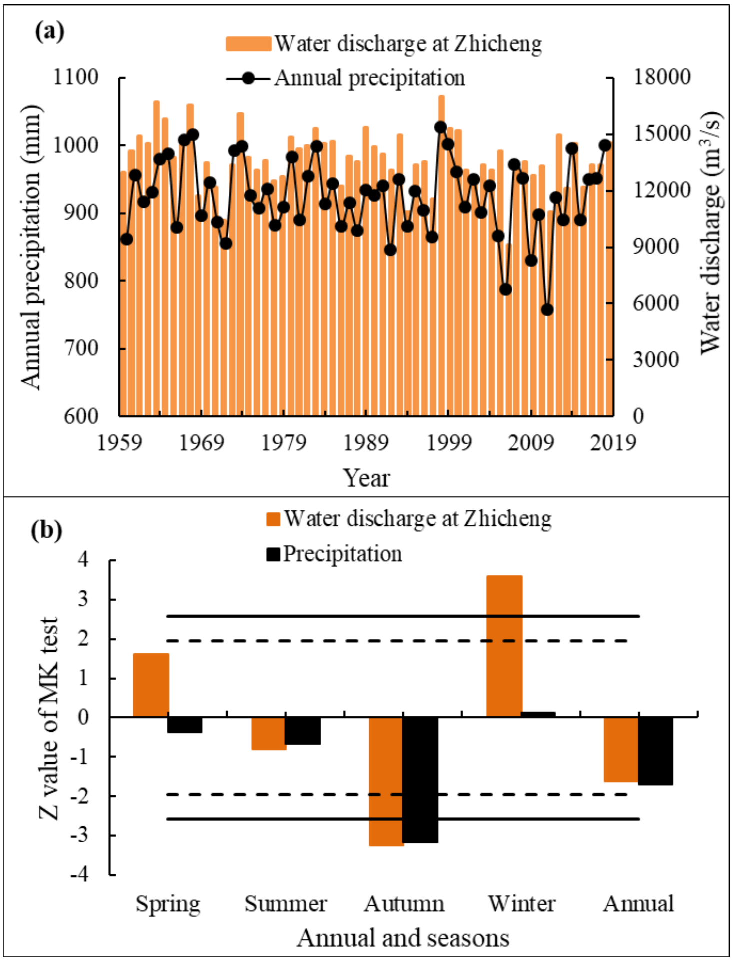

Figure 4. *Temporal trend changes in the annual-seasonal precipitation and water discharge at Zhicheng. (a) Annual precipitation and water discharge, (b) trends of the annual and seasonal precipitation and water discharge with the MK test. Horizontal dashed lines and solid lines in (b) denote confidence levels of 95% and 99% respectively*

Annual and seasonal water discharge trends at Zhicheng

Variations of the annual and seasonal water discharge at Zhicheng in the mainstream of Yangtze River are detected based on the observed data from 1960 to 2018 (*Fig. 4*). The annual average water discharge during 1960–2018 was 13,698.12 m^3/s, with a range from 12,995.85 m^3/s to 17,005.78 m^3/s (*Fig. 4a*). The annual average water discharge shows no significant decreasing trend and decreases by an average of 28.01

m^3/s every year (*Fig. 4*). The seasonal water discharge time series exhibited different change trends (*Fig. 4b*). Water discharge shows an upward trend in spring and a downward trend in summer, with no statistically significant levels. However, a decreasing trend in autumn and an increasing trend in winter were detected with a 99% confidence level.

Annual and seasonal water discharge trends at the JTO

The changes of annual and seasonal water discharge at the JTO are shown in *Figure 5*. The annual and seasonal water discharge at different stations fluctuated and decreased from 1960 to 2018. The annual average water discharge at Xinjiangkou, Shadaoguan, Mituosi, Ouchi (kang), and Ouchi (guan) decreased by an average of 7.15, 6.42, 8.29, 1.91, and 27.91 m^3/s every year, respectively. Before the 1970s, the average water discharge at Ouchi (guan) was significantly larger than at the other outlets, whereas it was smaller than that at Xinjiangkou after the 1970s (*Fig. 5a*). The seasonal water discharge dramatically fluctuated throughout the year at all stations. More than 90% of water discharge at all stations occurred in summer and autumn. In winter, water discharge at the JTO, except at Xinjiangkou, almost presented a zero-water discharge state after the 1970s (*Figs. 5b–f*).

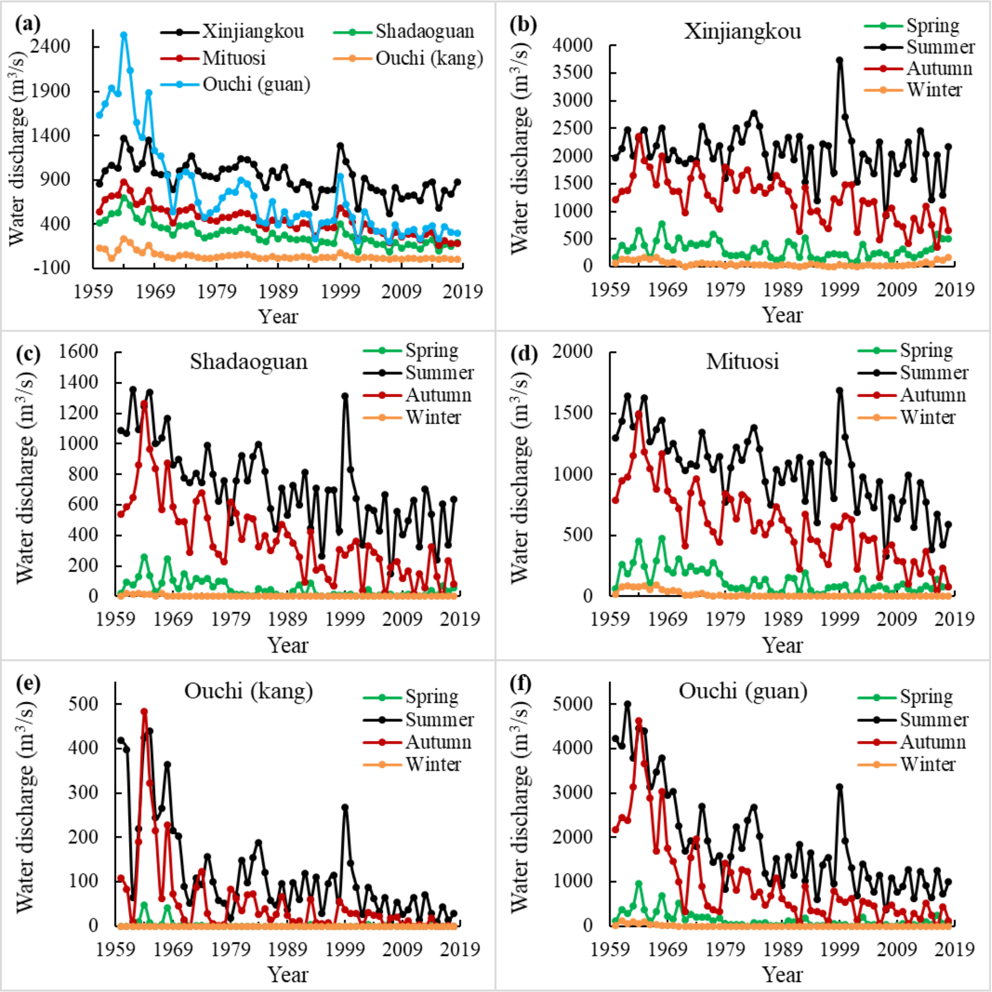

Figure 5. *Changes in the annual and seasonal water discharge at the JTO during 1960–2018. (a) Annual water discharge, (b–f) seasonal water discharge at different stations*

The annual and seasonal water discharge except at Xinjiangkou, in summer exhibited significant downward trends with a 99% confidence level (*Fig. 6*). The consistent trend results of annual and seasonal water discharge indicated that they might experience similar driving factors.

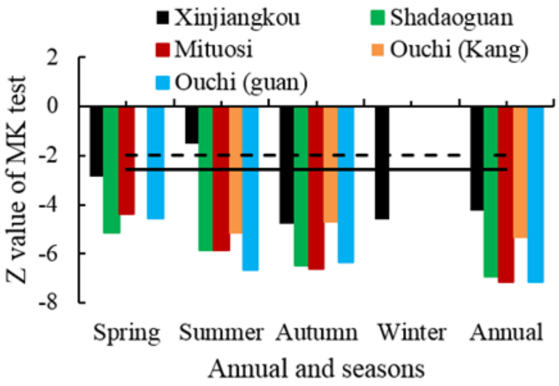

Figure 6. *Temporal trend changes in the annual and seasonal water discharge at the JTO with the MK test during 1960–2018. Horizontal dashed lines and solid lines denote confidence levels of 95% and 99% respectively*

Abrupt change point in annual-seasonal precipitation and water discharge

The Pettitt test was employed to detect abrupt change points in precipitation and water discharge for the control hydrological stations at the trunk stream of the Yangtze River and at the JTO during 1960–2018. The results are shown in *Table 2*. Only precipitation in autumn exhibited a downward abrupt change occurring in 1989. For the mainstream of Zhicheng, the water discharge in autumn and winter displayed significant abrupt changes in 1990 and 1999 with confidence levels of 99% and 95% respectively. On the other hand, every spring and summer, no significant abrupt changes occurred during 1960–2018. For the five control hydrological stations at the JTO, except water discharge in summer at Xinjiangkou and in spring at Ouchi (kang), significant abrupt changes were found in the annual and seasonal water discharge time series. All the stations at the JTO showed consistent outcomes with the test in spring (1977), summer (1982), and autumn (1989), whereas the abrupt stating times in annual and in winter were displayed differently. In general, abrupt stating times occurred mainly around 1980 and 1990. In particular, the abrupt stating times of the Ouchi (kang) and Ouchi (guan) at the Ouchi outlet were earlier than those of other outlets. Under the same conditions of the upstream, the change heterogeneity and inconsistency of annual and seasonal water discharge at the JTO indicated that local human activities affected the amount of water discharge in a complex way.

Impact of human activities and climate change on water exchange

The water exchange changes at the JTO have complex dynamic processes, which are not only closely associated with alterations in the hydrological regimes and channel morphology of the mainstream near the JTO, but also related to the scouring and silting changes in the diversion channels (Lu et al., 2012).

Precipitation and human activities in the upstream of Zhicheng caused the downstream water discharge changes, while water discharge changes at Zhicheng affected the amount of water exchange at the JTO. The decreasing trend of the average annual water discharge at the mainstream of Zhicheng was consistent with the annual precipitation change. This result is in agreement with previous findings. Chen et al. (2017) and Gao et al. (2012) used different methods to demonstrate that the annual streamflow at Yichang had a decreasing trend and confirmed that the decrease in annual precipitation was the primary driver. However, the seasonal change trends between the precipitation and the water discharge at Zhicheng displayed a complicated condition (*Fig. 4*).

Table 2. *Results of the Pettitt test for abrupt change points in the annual-seasonal precipitation and water discharge*

Type	Station name	Time scale	Change points	p value	Significance level
Precipitation	–	Annual	1984	0.3715353	–
		Spring	1978	0.3949851	–
		Summer	2003	0.9989329	–
		Autumn	1989	0.0007483	0.01
		Winter	2008	0.3949851	–
Water discharge	Zhicheng	Annual	2000	0.2811883	–
		Spring	2001	0.5568367	–
		Summer	2000	0.4449031	–
		Autumn	1989	0.0055008	0.01
		Winter	1999	0.0248369	0.05
	Xinjiangkou	Annual	1990	0.0001550	0.01
		Spring	1977	0.0007483	0.01
		Summer	2000	0.1400187	–
		Autumn	1989	0.0000104	0.01
		Winter	1979	0.0004053	0.01
	Shadaoguan	Annual	1985	0.0000015	0.01
		Spring	1977	0.0000038	0.01
		Summer	1982	0.0000351	0.01
		Autumn	1989	0.0000035	0.01
		Winter	1979	0.0000007	0.01
	Mituosi	Annual	1985	0.0000028	0.01
		Spring	1977	0.0000020	0.01
		Summer	1982	0.0000480	0.01
		Autumn	1989	0.0000058	0.01
		Winter	1983	0.0000002	0.01
	Ouchi (kang)	Annual	1993	0.0028987	0.01
		Spring	1973	0.0531960	0.01
		Summer	1982	0.0000480	0.01
		Autumn	1988	0.0036449	0.01
		Winter	Dried	Dried	–
	Ouchi (guan)	Annual	1985	0.0000053	0.01
		Spring	1977	0.0000041	0.01
		Summer	1982	0.0000088	0.01
		Autumn	1989	0.0000277	0.01
		Winter	1974	0.0000411	0.01

To further address the reasons for the seasonal water discharge changes at Zhicheng, the DMCs were plotted to show the relationship between the precipitation and the water discharge (*Fig. 7*). Abrupt changes in the DMCs are inapparent, especially in summer (*Fig. 7*). In spring and winter, similar with precipitation, water discharge after the transition years was larger than the before in the DMCs. In autumn, water discharge after the transition years was smaller than the before. These results on the seasonal trends and the DMC analysis indicated that the seasonal relationship between water discharge and precipitation had been disturbed by human activities. The operations of reservoirs and dams changed the distribution of inner-annual water discharge downstream. For example, the Three Gorges Reservoir increased low flow in the winter and decreased flood flow in summer since 2003 (Gao et al., 2012). The implementation of water–soil conservation caused a decrease in streamflow from the upper Yangtze River Basin (Yang et al., 2015).

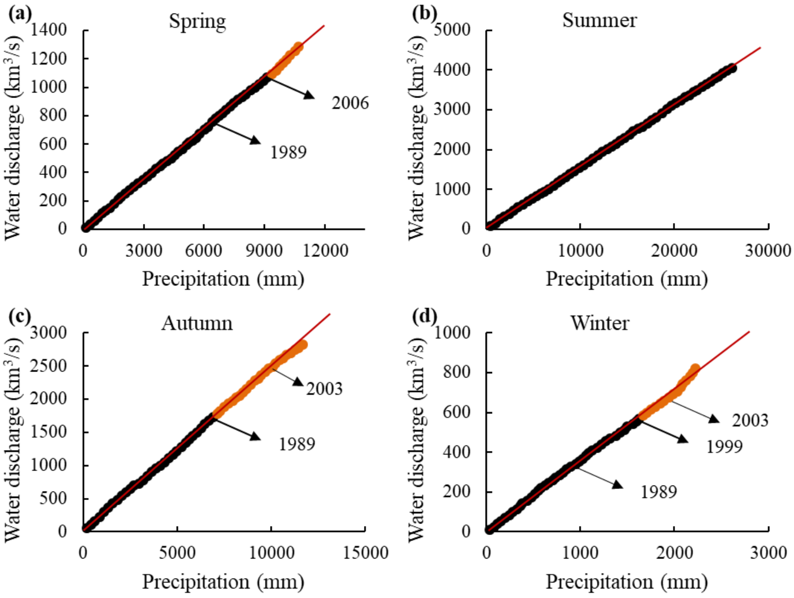

Figure 7. *DMC analysis between precipitation and water discharge at Zhicheng in different seasons*

The annual and seasonal trends of water discharge at the JTO were incompletely homologous to the hydrological variations at the mainstream of Zhicheng (*Figs. 4b* and *6*) because of alterations in the channel morphology (Lai et al., 2014b). The operations of reservoirs and dams trapped a large amount of sediment yield, especially after the operation of Gezhou Dam in 1981 (Zhang et al., 2006; Yang et al., 2014; Gao et al., 2015a, b). The implementation of water–soil conservation also caused a distinct in sediment yield from the upper Yangtze River Basin (Wang et al., 2011). Sediment yield decrease caused the channel erosion in the mainstream channel (Yua et al., 2018). The channel erosion resulted in the lowering water level with the same water discharge (*Figs. 8a*) which decreased the water level differences between the mainstream and the JTO, and resulted in the decline of water diversion ability. Meanwhile, the water level with the same water discharge at the JTO generally shifted up (*Figs. 8b–f*) because of the deposition at the diversion channel at the JTO. The alterations of the channel morphology counteracted the increase in water discharge of the mainstream and resulted in increased zero-discharge days at the JTO (Chang et al., 2010). Under the same precipitation and human activity conditions in the upper stream, the reduced magnitudes of water discharge at the different outlets during 1960–2018 were also different due to the different magnitudes of the scouring and silting changes in the diversion channels (*Figs. 8b–f*). River channel cut-offs caused strong channel erosions in the lower Jingjiang River and relative deposition in the diversion channels (Qin et al., 2013).

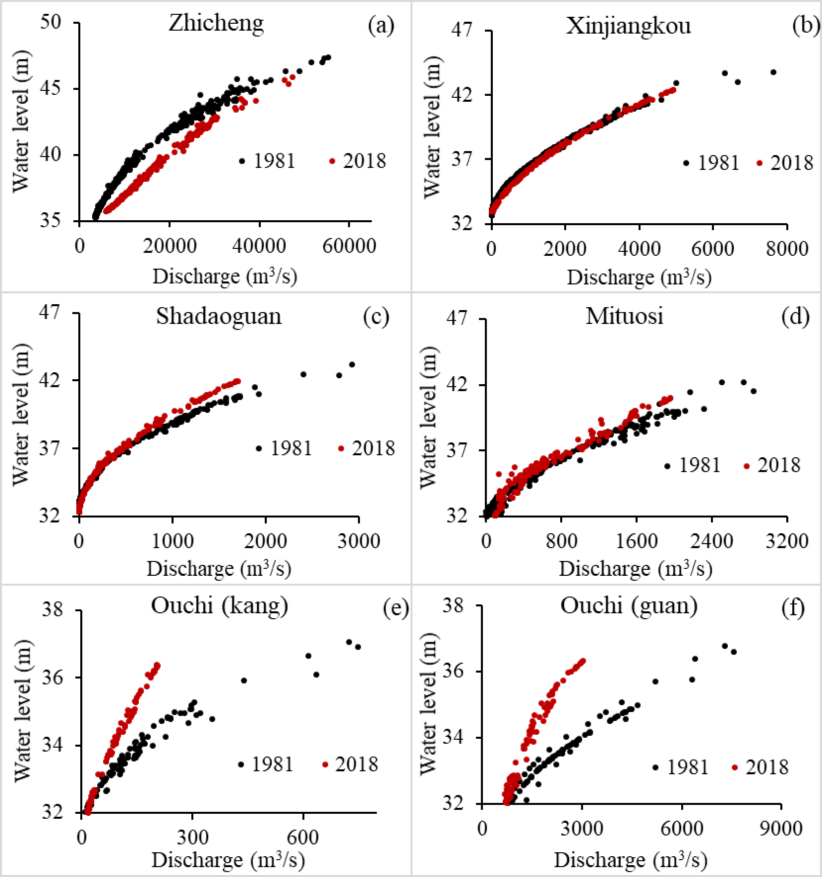

***Figure 8.** Rating curves between water level and discharge at Zhicheng and the JTO after the 1981*

Regression analysis for quantifying the influences of precipitation and human activities on the water exchanges at the JTO

Regression analysis was used to quantify the relative contributions of precipitation and human activities to water exchanges at the JTO. The correlation equations are established as shown in *Equations 8–13* based on data observed in the reference period 1960–1966. Their significance levels are as follows:

$$Q_Z = 4.775P + 68.303, \qquad R^2 = 0.7837, P = 0.002 \tag{Eq.8}$$

$$Q_X = 0.124P - 232.06, \qquad R^2 = 0.984, P < 0.001 \tag{Eq.9}$$

$$Q_S = 0.0727Q_Z - 171.11, \qquad R^2 = 0.964, P < 0.001 \tag{Eq.10}$$

$$Q_M = 0.08Q_Z - 146.98, \qquad R^2 = 0.919, P < 0.001 \qquad \text{(Eq.11)}$$

$$Q_{OK} = 0.0308Q_Z - 96.609, \qquad R^2 = 0.763, P = 0.01 \qquad \text{(Eq.12)}$$

$$Q_{OG} = 0.2395Q_Z - 507.04, \qquad R^2 = 0.886, P = 0.002 \qquad \text{(Eq.13)}$$

where Q_Z is the streamflow at Zhicheng; P is the basin-averaged annual precipitation above Zhicheng; and Q_X, Q_S, Q_M, Q_{Ok}, and Q_{OG} are the amounts of water discharge at Xingjiangkou, Shadaoguan, Mituosi, Ouchi (kang), and Ouchi (guan), respectively.

The modeling results are validated by comparing the observed and estimated water discharges in the reference period 1960–1966, as shown in *Table 3*. The calculated water discharges are consistent with the measured values. The comparison between the observed and the estimated is shown in *Figure 9*. The precipitation changes played a main role in the decreasing of streamflow in the the Yangtze River (*Table 4*), an effect that is consistent with previous studies (Chen et al., 2014; Yang et al., 2015; Zhao et al., 2015). However, the impact of human activities was gradually intensified and had a dominant status on the water discharge at the JTO. The impact degrees of human activities on water discharge were different at each outlet (*Fig. 9*). *Table 4* shows the contributions of human activities and climate change to impacts in water discharge from 1967 to 2018. At Xinjiangkou, human activities were responsible for 57.20% of the changes. In the other JTO stations, the impact of human activities on streamflow were 84.01% at Shadaoguan, 83.69% at Mituosi, 84.02% at Ouchi (kang), and 89.21% at Ouchi (guan). These results indicated that human activities played a more important influence than climate change in the decrease of water discharge at the JTO.

Table 3. *Results of regression analysis for the water discharge at the JTO in the reference period 1960–1966*

Station name	**Duration**	**Water discharge (10^8 m^3/yr)**		**R^2**
		Observed	**Estimated**	
Zhicheng	1960–1966	4,098.371	4,149.261	0.784
Xinjiangkou	1960–1966	342.510	337.368	0.853
Shadaoguan	1960–1966	165.892	163.524	0.778
Mituosi	1960–1966	223.622	220.741	0.912
Ouchi (kang)	1960–1966	46.104	46.022	0.715
Ouchi (guan)	1960–1966	602.649	593.825	0.850

Table 4. *Impact of climate change and human activities on water discharge at the JTO*

Station name	**Period**	**Water discharge (10^8 m^3/yr)**			**Impact of climate change (%)**	**Impact of human activities (%)**
		Observed	**Estimated**	**Total change**		
Zhicheng	1967–2018	4,689.641	4,636.272	390.427	62.63	37.37
Xinjiangkou	1967–2018	287.322	318.890	55.188	42.80	57.20
Shadaoguan	1967–2018	82.630	152.579	83.261	15.99	84.01
Mituosi	1967–2018	132.873	208.820	90.749	16.31	83.69
Ouchi (kang)	1967–2018	10.236	40.374	35.868	15.98	84.02
Ouchi (guan)	1967–2018	190.279	558.136	412.370	10.79	89.21

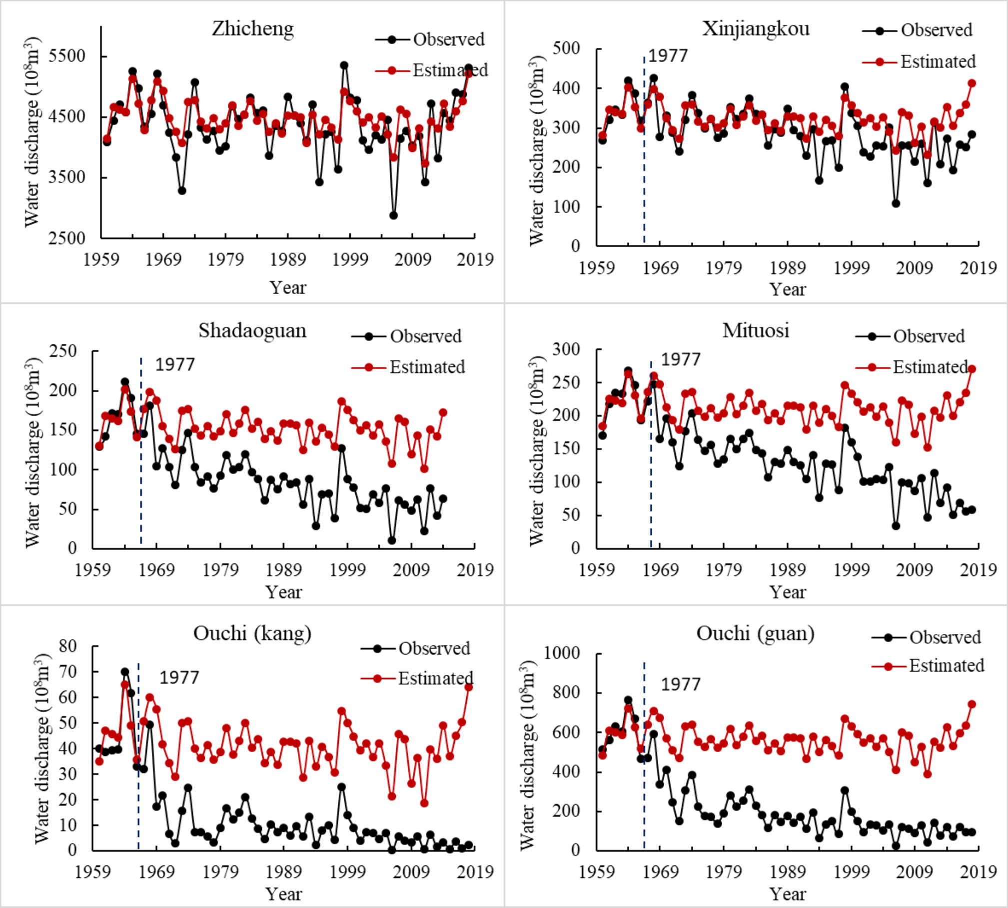

Figure 9. *Comparison between the observed mean annual streamflow and the estimated mean annual streamflow at the JTO with the regression analysis. The period 1960–1966 was the baseline period, and the period 1967–2018 was the prediction period*

Conclusions

This study utilized the MK Pettitt tests to analyze the spatial–temporal variations of precipitation and water discharge at the mainstream and at the JTO from 1960 to 2014. In addition, the impacts which human activities and climate change on water exchange between Yangtze River and Dongting Lake were assessed using the DMC method and regression analysis. Conclusions were summarized as follows:

(1) Precipitation change trends presented no statistical significance, except in autumn with a significant decrease at the 99% confidence level. Water discharge at Zhicheng showed a decreasing trend in autumn and an increasing trend in winter with a 99% confidence level. However, other periods displayed no significant trend changes. Annual and seasonal water discharge at the JTO, except at Xinjiangkou in summer, all exhibited significant downward trends with a 99% confidence level. The lack of consistent trends in the seasonal precipitation and water discharge at Zhicheng and at the JTO indicated that the seasonal relationships between them had been disturbed by human activities.

(2) Abrupt stating years of all the stations at the JTO were mainly around 1980 and 1990, and the Ouchi (kang) and Ouchi (guan) at the Ouchi outlet were earlier than the other stations. Under the same conditions of climate changes and human activities in the

upstream of the Yangtze River, the change heterogeneity and inconsistency of annual and seasonal water discharge at the JTO indicate that local channel cut-off projects affect the amount of water discharge in a complex manner.

(3) Human activities had a dominant effect on the water discharge at the JTO, and the impact degrees of human activities on water discharge were different at each station. During 1967–2018, the impact of human activities on water discharge at Xinjiangkou were 57.20%. The impact of human activities on water discharge were 84.01% at Shadaoguan, 83.69% at Mituosi, 84.02% at Ouchi (kang), and 89.21% at Ouchi (guan).

(4) This research is an important step toward understanding the impact of climate changes and human activities on streamflow reduction at the JTO and provides an important scientific basis for the optimization control of the Yangtze River–Dongting Lake relationship.

Acknowledgements. This work is supported by the National Natural Science Foundation of China (41601041) and the Key Research Program of the Chinese Academy of Sciences (KFZD-SW-318). We thank Dr. Shi Kun for his detailed and helpful comments on the manuscript.

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